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A STUDY OF THE EFFECT OF BRUSHING THE HEAT TRANSFER SURFACE IN THE PRESENCE OF A LIQUID CONDENSATE OR A SOLID SUBLIMATE

PART 1. THE REMOVAL OF A LIQUID FROM A GAS PHASE

PART 2. THE REMOVAL OF A SOLID FROM A GAS PHASE

W. L. Anderson, B.Sc.
Chemical Engineering.

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The undersigned hereby certify that they have read and recommend to the COMMITTEE ON GRADUATE STUDIES for acceptance, a Thesis entitled

A STUDY OF THE EFFECT OF BRUSHING THE HEAT TRANSFER SURFACE IN THE PRESENCE OF A LIQUID CONDENSATE OR A SOLID SUBLIMATE

Submitted by William Lindsay Anderson, B.Sc., in partial fulfilment of the requirements for the degree of Master of Science.

PROFESSOR

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A STUDY OF THE EFFECT OF BRUSHING THE HEAT TRANSFER SURFACE IN THE PRESENCE OF A LIQUID CONDENSATE OR A SOLID SUBLIMATE

PART 1. THE REMOVAL OF A LIQUID FROM A GAS PHASE

PART 2. THE REMOVAL OF A SOLID FROM A GAS PHASE

- by -

William Lindsay Anderson, B.Sc.

Shell Oil Fellowship

University of Alberta

A T H E S I S

Submitted to the University of Alberta in partial fulfilment of the requirements for the degree of Master of Science in Chemical Engineering.

Edmonton, Alberta July, 1948

A B S T R A C T

A process is outlined whereby heat transfer can be increased two to five times by the continuous removal of a condensate or a sublimate mechanically as formed on a heat transfer surface.

A pyrex apparatus is used, employing a close-fitting brush rotated by an electrical stirrer.

Condensate tests using water as the condensate and sublimate tests using CO_2 as the sublimate are run with and without brushing.

The results are plotted in graphical form.

W. L. ANDERSON

April 24, 1924

PREFACE AND ACKNOWLEDGEMENTS

The investigations described in this thesis were carried out in the laboratories of the Chemical Engineering Department of the University of Alberta, under the supervision of Dr. J. A. Taylor, Department Head, to whom the writer wishes to acknowledge his indebtedness for advice and assistance throughout the work.

He also wishes to thank E. Newman and other members of the Chemical Engineering and Chemistry Departments for their co-operation and helpful suggestions.

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INTRODUCTION

INTRODUCTION AND LITERATURE REVIEW

In many heat transfer cooling operations a change of phase often occurs. Thus a liquid condensate or a solid deposit is formed which builds up on the heat transfer walls of the apparatus and constitutes a serious resistance to heat transfer. It may even be necessary to shut down the process after a time and either warm up the unit or else scrape off the deposit.

The problem of this investigation was to study the increase in the heat transfer brought about by the removal of the surface deposit as formed from a gas phase. The method used was a continuous brushing of the heat transfer surface.

Several processes could be readily adopted to this type of heat exchanger, for example; air drying, air conditioning, production of solid carbon dioxide from flue gases.

C.W. Vogt in 1928 designed a tube to handle liquid heat transfer problems. Some of the patents covering his investigations are listed in the appendix. These patents include an apparatus for the mixing and freezing of ice cream, the freezing of fruit juices and certain oleoginous comestibles such as shortening or margarine. Vogt's apparatus consisted of two concentric tubes through which the product and heat transfer medium pass, and a central mutator shaft revolving in the inner product tube. Scraper blades are mounted on the mutator shaft so that they cut close to the heat transfer wall and mix the product being pumped through the tube.

While Vogt's apparatus was developed for transformations from the liquid phase, the present apparatus was designed for studying transformations from the gas phase.

THEORY

THEORY

In the majority of heat transfer problems met in industrial practice, heat is being transferred from one fluid through a solid wall to another fluid. With this concept in mind, Newton found that the rate, dq of heat transfer was directly proportional to the over-all difference between the temperatures of the warmer and the colder fluids ΔT, and to the heat transfer surface dA.

$$dq = UdA\Delta T. \qquad (1)$$

The proportionality factor U is called the local over-all coefficient of heat transfer.

In computing U, one may use the area of heating surface dA' the area of cooling surface dA" or the logarithmic mean surface area of dAw. Since in this apparatus the glass walls are quite thin, the area corresponding to the arithmetic mean diameters was used.

Referring to Fig.6 . Temperatures may be plotted as ordinates against distance from the hottest point in the warmer fluid to the temperature of the cold fluid.

As a result of the difference in temperature between the hot fluid and the wall, t" - ts" or $\Delta t"$, the heat flow rate dq is proportional to t" and to the heat transfer area dA"

$$\therefore dq = h"dA"\Delta t" \qquad (2)$$

The proportionality factor h' is called the local individual coefficient of heat transfer.

HEAT TRANSFER THROUGH SOLID CONDUCTORS.

The rate of conduction through the retaining wall of thickness xw is given by the equation

$$dq = \frac{Kw\ dAw\ \Delta tw}{xw} \qquad (3)$$

The heat also flows by conduction at the same rate dq through the deposit eg. (solid carbon dioxide) having a thickness x_d on the cooling surface dA'.

$$dq = \frac{K_d \, dA' \, \Delta t_d}{x_d} = h_d \, dA' \, \Delta t_d. \qquad (4)$$

As a result of the difference between the temperature of the outer surface of the deposit and the bulk temperature of the warm fluid, $t_d' - t'$ or $\Delta t'$, the local individual coefficient to the warm fluid is defined by the Newton relation

$$dq = h' \, dA' \, \Delta t'. \qquad (5)$$

Relation between local over-all and local individual coefficients.

By solving equations 2, 3, 4 and 5 for local individual temperature drops.

$\Delta t'' = d''/h''dA''$

$\Delta w = dqxw/KwdAw$

$\Delta t_d = dq/h_d dA$

$\Delta t' = dq/h'dA'$

Since dq is constant.

$$\Delta t = dq \left(\frac{1}{(h''dA''} + \frac{xw}{KwdAw} + \frac{1}{h_d dA'} + \frac{1}{h'dA'} \right) \qquad (6)$$

$$\Delta t = \frac{dq}{UdA}$$

$$\therefore \quad \frac{\Delta t}{dq} = \frac{1}{U_d A} = \frac{1}{h''dA''} + \frac{xw}{KwdAw} + \frac{1}{h_d dA''} + \frac{1}{h'dA'} \qquad (7)$$

For a particular U

$$\frac{1}{U} = \frac{dA}{h''dA} + \frac{xwdA}{KwdAw} + \frac{dA}{h_d dA''} + \frac{dA}{h'dA'} \qquad (8)$$

Since the thickness of the wall is small compared to the tube diameter.

$$\frac{1}{U} = \frac{1}{h''} + \frac{Xw}{Kw} + \frac{1}{h_d} + \frac{1}{h'} \qquad (9)$$

RESISTANCE CONCEPT

An overall resistance R_t may be defined for unit area dA.

$$R_t = \frac{1}{U} = R'' + Rw + R_d + R' \qquad (10)$$

Where $R'' = \frac{dA}{h'dA''}$

and $R_w = \frac{x_w dA}{K_w dA_w}$ etc.

Thus the individual thermal resistances are additive for flow of heat through a series of resistances.

$$\therefore \quad dq = \frac{\Delta t}{\frac{1}{UdA}} = \frac{\Delta t}{\frac{1}{h''dA''} + \frac{xw}{KwdAw} + \frac{1}{h_d dA'} + \frac{1}{h'dA'}}$$

COEFFICIENTS FOR SCALE DEPOSITS

The resistance of a scale deposit may be obtained from the relation

$$\frac{1}{h_d} = \frac{1}{U_d} - \frac{1}{U_c}$$

Where U_d is the over-all coefficient for the apparatus with the deposit present.

U_c is the overall coefficient after cleaning (brushing in this case).

h_d is the conductivity coefficient of the deposit (condensate or sublimate) removed.

Since the temperature of the warmer fluid changes as it passes through the apparatus, it is necessary to integrate the basic equation.

$dq = UdA\Delta t$. which applies to point conditions.

This equation may be integrated algebraically obtaining the familiar log. mean temperature difference.

$q_o = UA\Delta m$.

where Δm = log mean temperature difference.

$$\Delta m = \frac{\Delta_2 - \Delta_1}{2.303 \log \frac{\Delta_2}{\Delta_1}}$$

Where Δ_2 and Δ_1 are the driving force temperature differences at either end of the apparatus

Thus $U = \frac{Q}{A\Delta m}$.

The effect of the brushing was a continuous partial removal of the surface film as formed.

APPARATUS

FIG. NO. 1

HEAT TRANSFER APPARATUS FLOW SHEET

FIG. NO. 1

HEAT TRANSFER APPARATUS FLOW SHEET

(A) High pressure air line (100 psig)
(B) Pressure cylinder
(C) Carbon dioxide cylinder
(D) Low pressure air line
(E) Gas lift
(F) Wet test meter
(G) Bellows type gas meter
(H) Sulphuric Acid Dryer
(I) Phosphorus pentoxide - glass wool packed dryer
(J) Wet and dry bulb thermometer
(K) Manometer filled with n-butyl phthalate
(L) Vacuum flask
(M) Pyrex heat exchanger
(N) Brush
(O) Packing gland
(P) Mixmaster stirrer
(Q) Cold junction
(R) Potentiometer Voltmeter

Thermometers

(A) Wet Bulb
(B) Dry Bulb
(C) Inlet Air Temperature
(D) Copper-Constantan thermocouple - outlet air temperature

Valves

Control valves, "8" and "12"
Pinch cock valve "9"
Press reducing valves "5" and "6"
On and off valves 1, 2, 3, 4, 7, 10, 11, 13, 14, 15, 16, 17, 18, 19, 20.

HEAT TRANSFER APPARATUS
FLOW SHEET

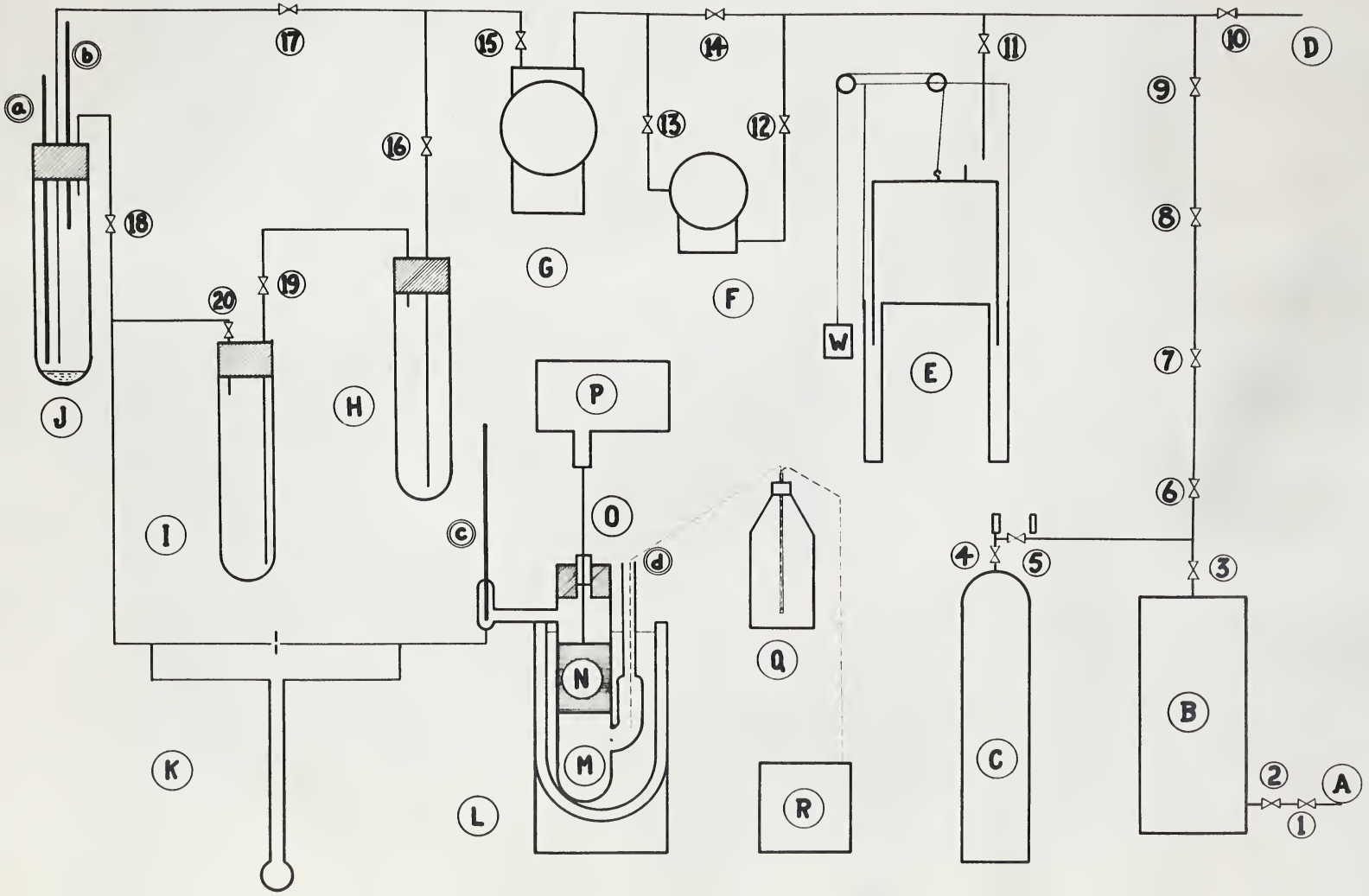


FIG. NO. 2

PHOTOGRAPH OF COMPLETE APPARATUS

FIG. NO. 2

FIG. NO. 3

PHOTOGRAPH READING INSTRUMENTS

FIG. NO. 3

FIG. NO. 4

PYREX HEAT EXCHANGER, ONE-HALF SCALE

PYREX

HEAT EXCHANGER

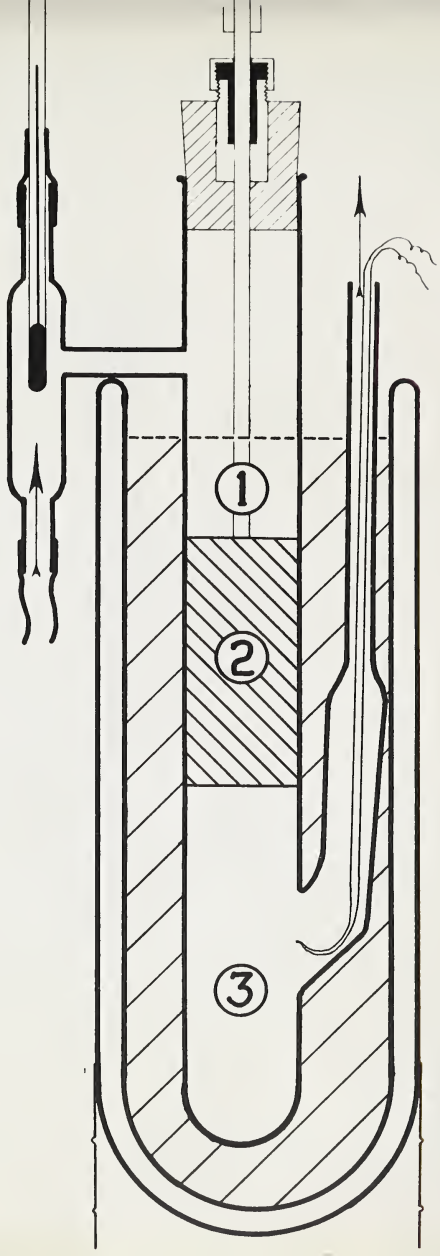


FIG. NO. 5

PHOTOGRAPH OF PYREX HEAT EXCHANGER

FIG. NO. 5

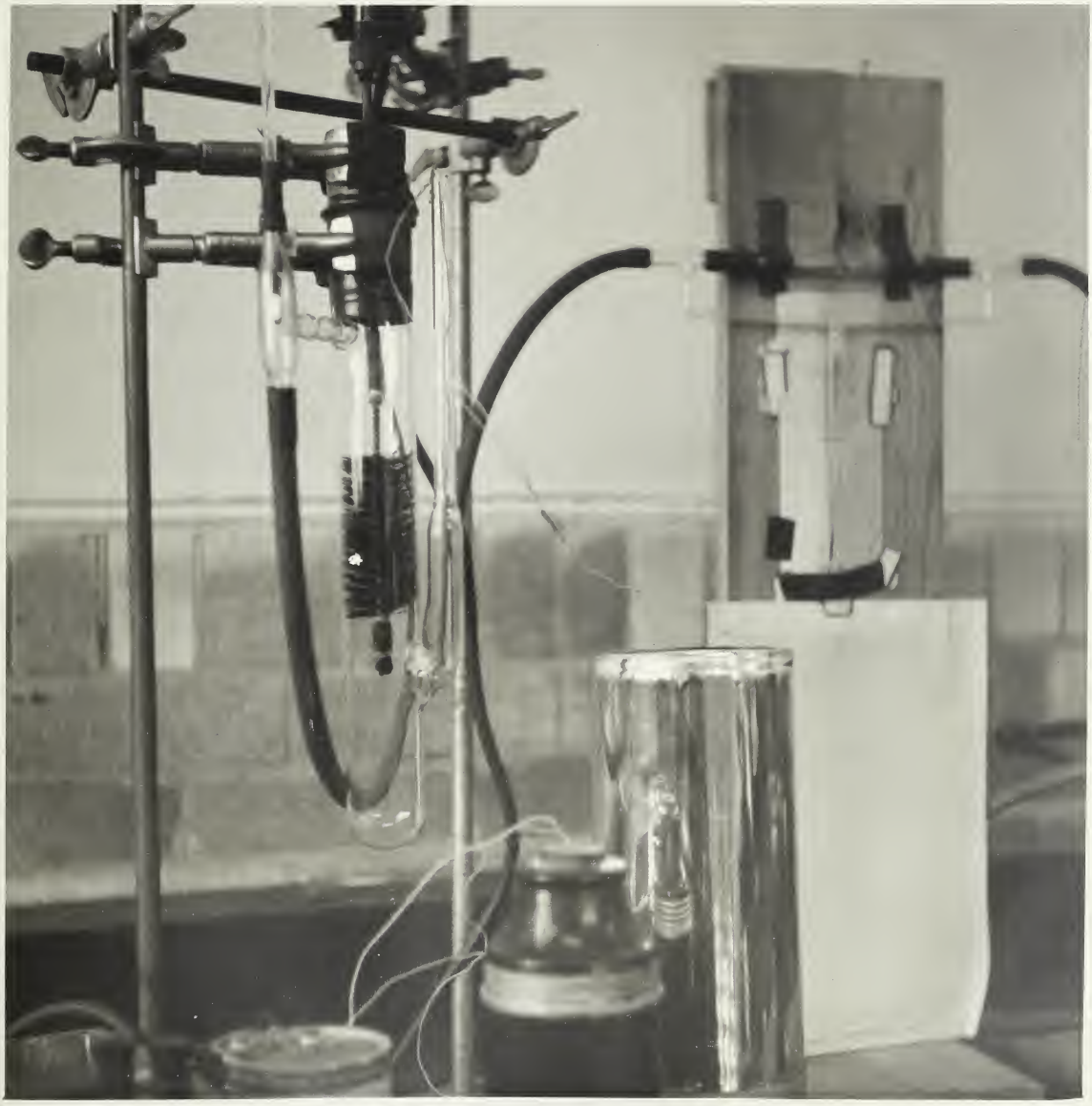


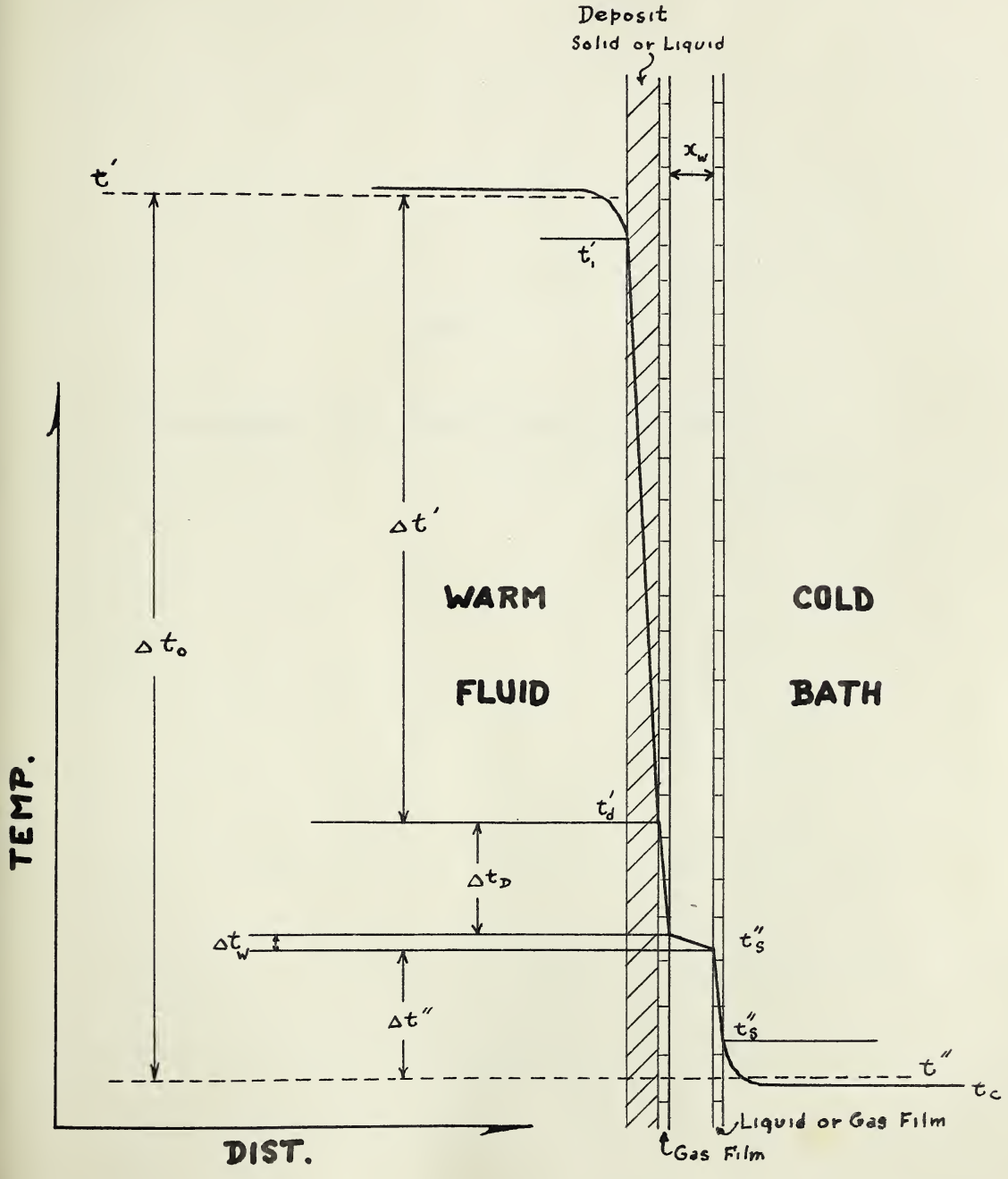
FIG. NO. 6

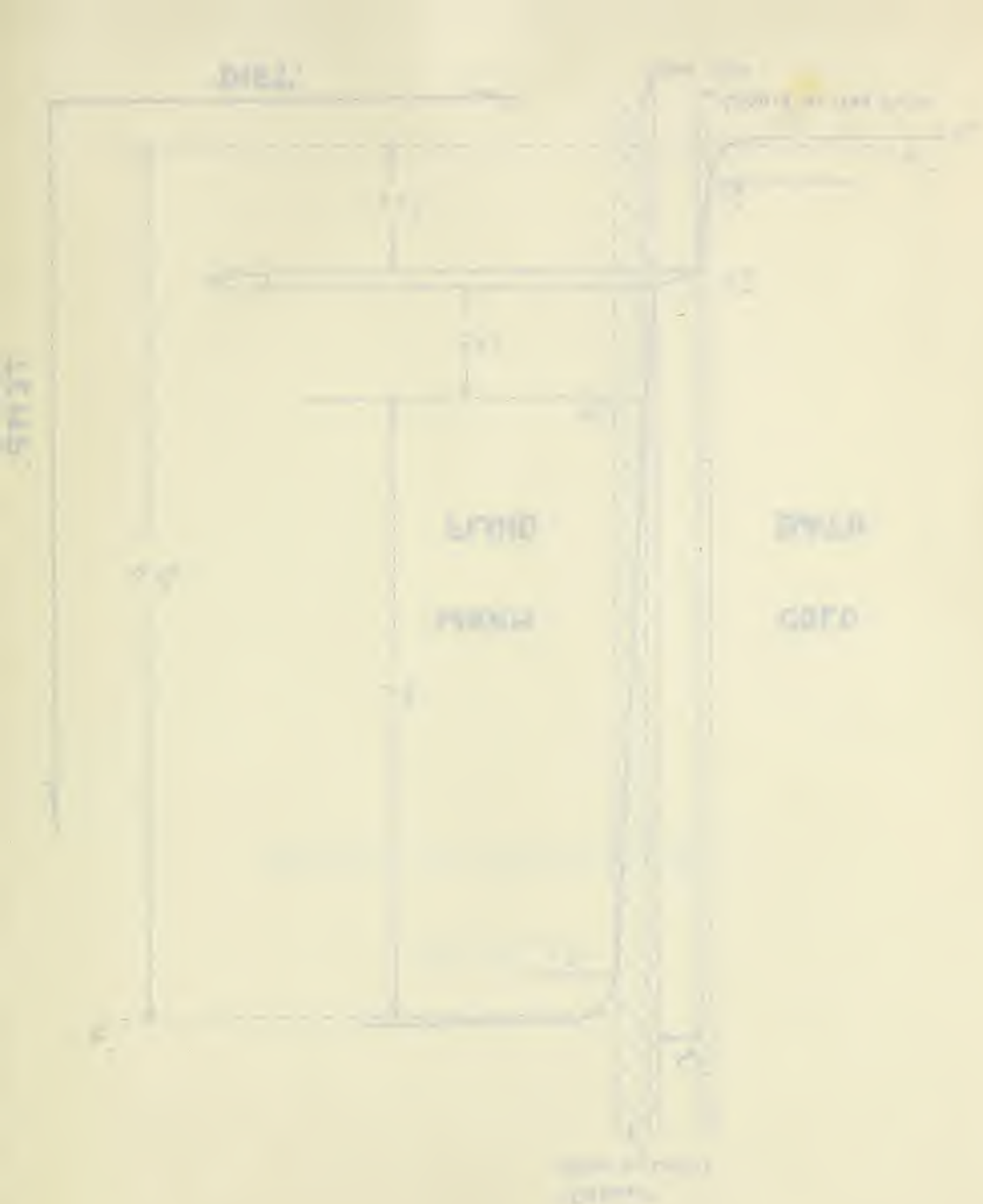
SECTION OF HEAT EXCHANGER WALL

SECTION OF HEAT EXCHANGER WALL

TEMPERATURE vs DISTANCE

POINT CONDITIONS





PART 1

THE REMOVAL OF A LIQUID FROM A GAS PHASE

EXPERIMENTAL PROCEDURE

1. THE REMOVAL OF A LIQUID FROM A GAS PHASE.

Ref. Fig.1

In these tests the liquid used was water, and the carrier gas, air from the low pressure air line "D" through valve "10".

During the run, valves 10,12, 13, 15, 17, 18, were open, and valves 9, 11, 14, 16, 20 were closed. Valve number "12" was used as the control valve to regulate the flow rate as measured on the manometer "K". The air flowed through valves "10" and "12" through the wet test volumetric meter "F" where it was saturated with water, through valve "13" through the bellows type gas meter "G", then through valves 15, 17. The near saturated gas then passed through the wet and dry bulb thermometer tube "J" where the actual humidity was determined, through valve "18" then through the orifice meter "k". The orifice meter manometer was filled with n-butyl phthalate. The wet gas then passed into the top of the pyrex heat exchanger "M" and out the bottom. The gas was cooled and the moisture caused to condense by the surrounding ice and water, both contained in the vacuum flask "L".

The temperatures involved were measured by the mercury thermometers a, b, c, and the copper-constantan thermocouple "d". "a" was the wet bulb, "b" the dry bulb used to obtain absolute humidity, "c" was used to measure inlet gas temperature to the heat exchanger and the thermocouple "d" was used to measure the outlet gas temperature. "Q" was an ice and water cold-junction for the thermocouple and "R" a potentiometer voltmeter used to indicate the outlet temperature readings in millivolts.

Tests were run with and without brushing at various flow rates between ten and seventy cubic feet per hour. A close fitting nylon brush "N" was used, rotated by a Mix master "P", operating through a packing gland "O". The motor speed was fairly constant (between 825 and 850 R.P.M.).

SAMPLE CALCULATION

WATER-CONDENSATION TESTS.

In these tests, the wet gas flow rate was obtained from the manometer differential "K" in Fig. 1. This manometer was calibrated at low flow rates by the wet test meter "F" in Fig. 1. (accuracy $\pm$ 0.2 percent), and by the bellows type gas meter (accuracy $\pm$ 0.5 percent) at high flow rates. The inlet air temperature was measured by the mercury thermometer "C"; the outlet temperature by the thermocouple "d". The absolute humidity was obtained from the wet and dry bulbs "a" and "b" respectively of Fig. 1, and use of the "Humidity Chart found in Walker Lewis McAdams and Gilliland" (See Author Index).

Each run tabulated is an overage of the data obtained on three separate tests, so that the ten runs shown are a composite of thirty separate tests.

As an example of the method of calculation used throughout, consider run #2. Table #1 and Fig. 9.

Temperature of the outlet gas in the case without brushing was 7.5 degrees centigrade.

Temperature of the outlet gas in the case with brushing was 2.5 degrees centigrade.

The flow rate was 17.7 cubic feet per hour, measured at inlet air temperature (25.2 degrees centigrade and at one atmosphere pressure).

Wet bulb reading was 23.6 degrees centigrade.

Dry bulb reading was 24.6 degrees centigrade.

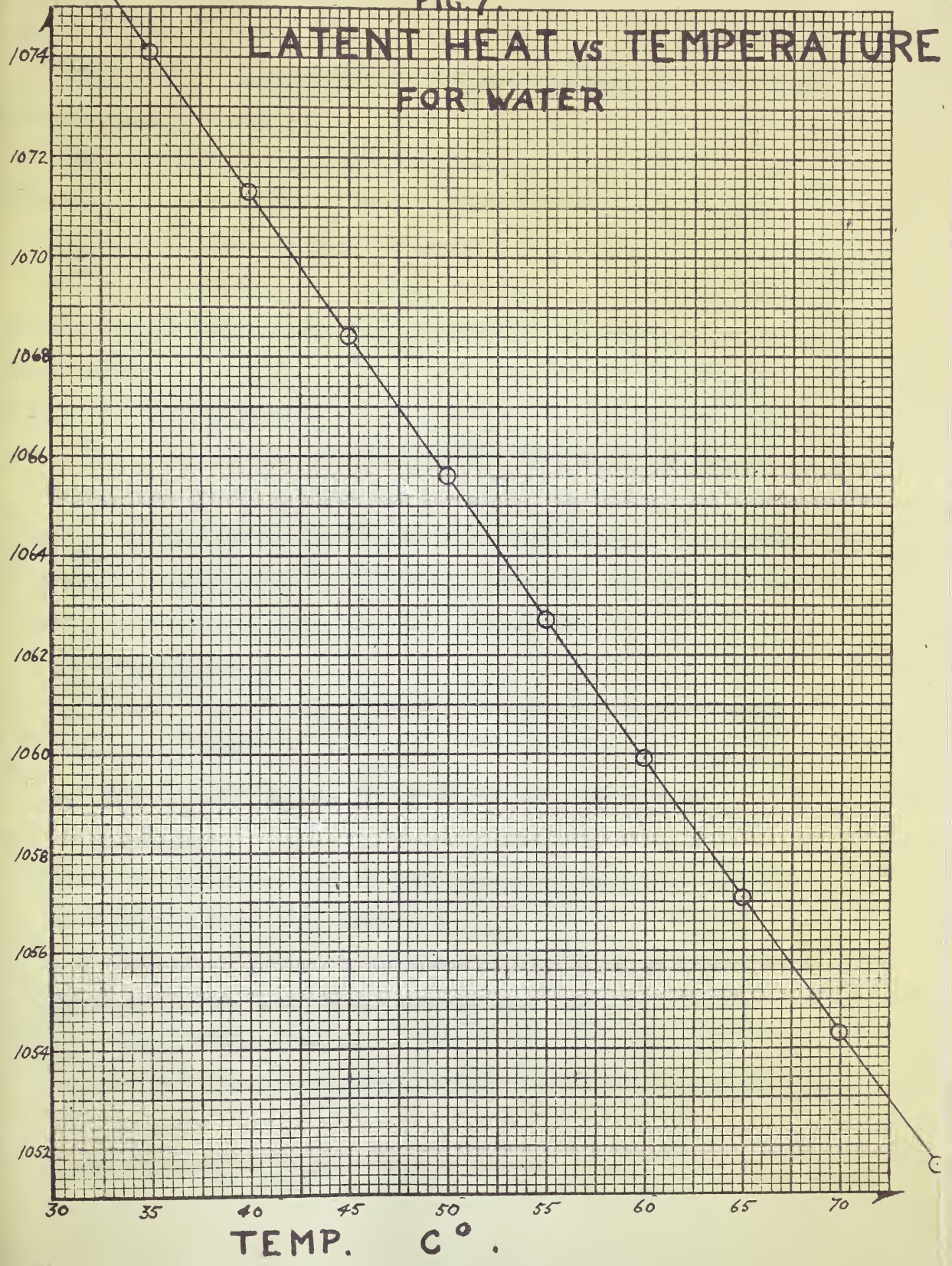
These gave inlet air humidity of 0.0196 and a relative humidity of 90 percent. The air density was then 0.0722 pounds per cubic foot.

The humidity of the outlet air at 7.5 degrees centigrade was 0.0071 pounds of

FIG. NO. 7

LATENT HEAT VS. TEMPERATURE FOR WATER

FIG. 7.


LATENT HEAT vs TEMPERATURE
FOR WATER
LATENT HEAT B.T.U./LB.
1074
1072
1070
1068
1066
1064
1062
1060
1058
1056
1054
1052
30
35
40
45
50
55
60
65
70
TEMP. C°.

water per pound of dry air.

The humidity of the outlet air at 2.5 degrees centigrade was 0.0049 pounds of water per pound of dry air.

Pounds of dry air = $\frac{17.7}{}$ X 0.0712 = 1.262

Pounds of water = 0.0196 X 1.262 = 0.0246 pounds per hour.

Consider first the case where the surface is not brushed.

The heat removed from the air to lower the temperature from 25.2 degrees centigrade at the inlet to 7.5 degrees centigrade at the outlet may be divided into two parts

(1) The sensible heat Q_s.

(2) The latent heat of condensation of the water present in the air.

Providing an average specific heat is used for the varying conditions of humidity and temperature over the inlet-outlet temperature interval, the moisture could be considered to condense at the outlet temperature, and the latent heat at this temperature used without much error in the calculation.

(1) Sensible Heat.

Q_s = pounds of air per hour X average specific heat X the inlet-outlet temperature difference.

Q_s = 1.262 X 0.248 X (25.2 - 7.5) X 1.8 = 9.98 B.T.U. per hour.

(2) Latent Heat.

Latent heats at various outlet temperatures were obtained from a plot of Latent Heat vs Temperature; see Fig. 7.

Q_l = pounds of air per hour X the latent heat at outlet gas temperature X difference between inlet and outlet humidity.

Q_l = 1.262 X 1068.0 X (0.0196 - 0.0071) = 16.82 B.T.U. per hour.

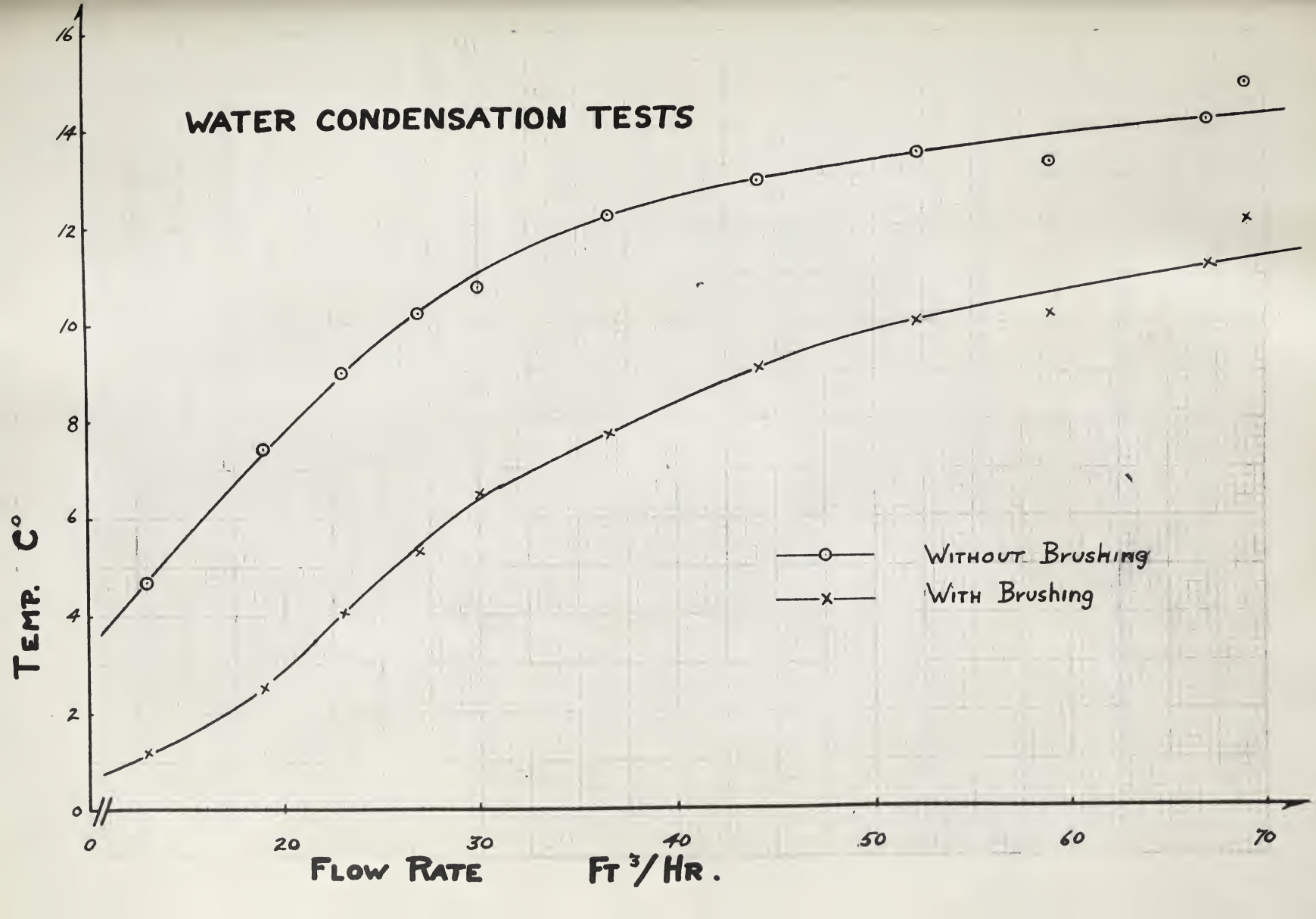
Therefore the total heat transferred without brushing = 9.98 + 16.82 = 26.80 B.T.U. per hour.

The Heat Transfer Coefficient U without brushing is $U = \frac{Q}{A \Delta m.}$

FIG. NO. 8

TEMPERATURE VS. FLOW RATE

WATER CONDENSATION TESTS


WATER CONDENSATION TESTS
TEMP. C°
FLOW RATE FT³/HR.
WITHOUT BRUSHING
WITH BRUSHING
0
2
4
6
8
10
12
14
16
20
30
40
50
60
70

where Q is the total heat transferred in B.T.U. per hour

A is the total heat transfer area in square feet

Δm is the logarithmic mean temperature difference in degrees F.

$$m = \frac{\Delta_2 - \Delta_1}{\text{ln.} \frac{\Delta_2}{\Delta_1}}$$

Δ_2= heat transfer driving force at the inlet end

Δ_1= heat transfer driving force at the outlet of the pyrex heat exchanger.

$\Delta_2 = (25.2 - 0) = 25.2$ degrees Centigrade.

$\Delta_1 = (7.5 - 0) = 7.5$ degrees Centigrade.

Therefore $\Delta m = \frac{25.2 - 7.5}{2.303 \log \frac{25.2}{7.5}} = 14.5$ degrees Centigrade.

Then $U = \frac{26.80}{0.2438 \times 14.5 \times 1.8} = 4.22$ B.T.U. per hour. feet squared, degrees F.

U Not Brushed = 4.22

Now consider Fig.9. "A" is the inlet temperature, "B" the outlet temperature. "D" is the log mean temperature difference between "A" and "B". In a similar manner the log mean temperature between "E" and "D" and between "D" and "B" was found. By continuing this process, the entire heat transfer curve without brushing was calculated from the two original points "A" and "B".

Now consider the case where the surface is brushed, Run #2, Table 1, Fig.9 . Since only area "2", Fig.9 . is brushed, the heat transfer coefficient for areas "1" and "3" are assumed to be the same with and without brushing, providing the flow rate, absolute humidity, and inlet temperature remain constant.

Point "E" in Fig.9 . was located by the intersection of the border of "A_1", and "A_2" and the heat transfer curve A-D-B.

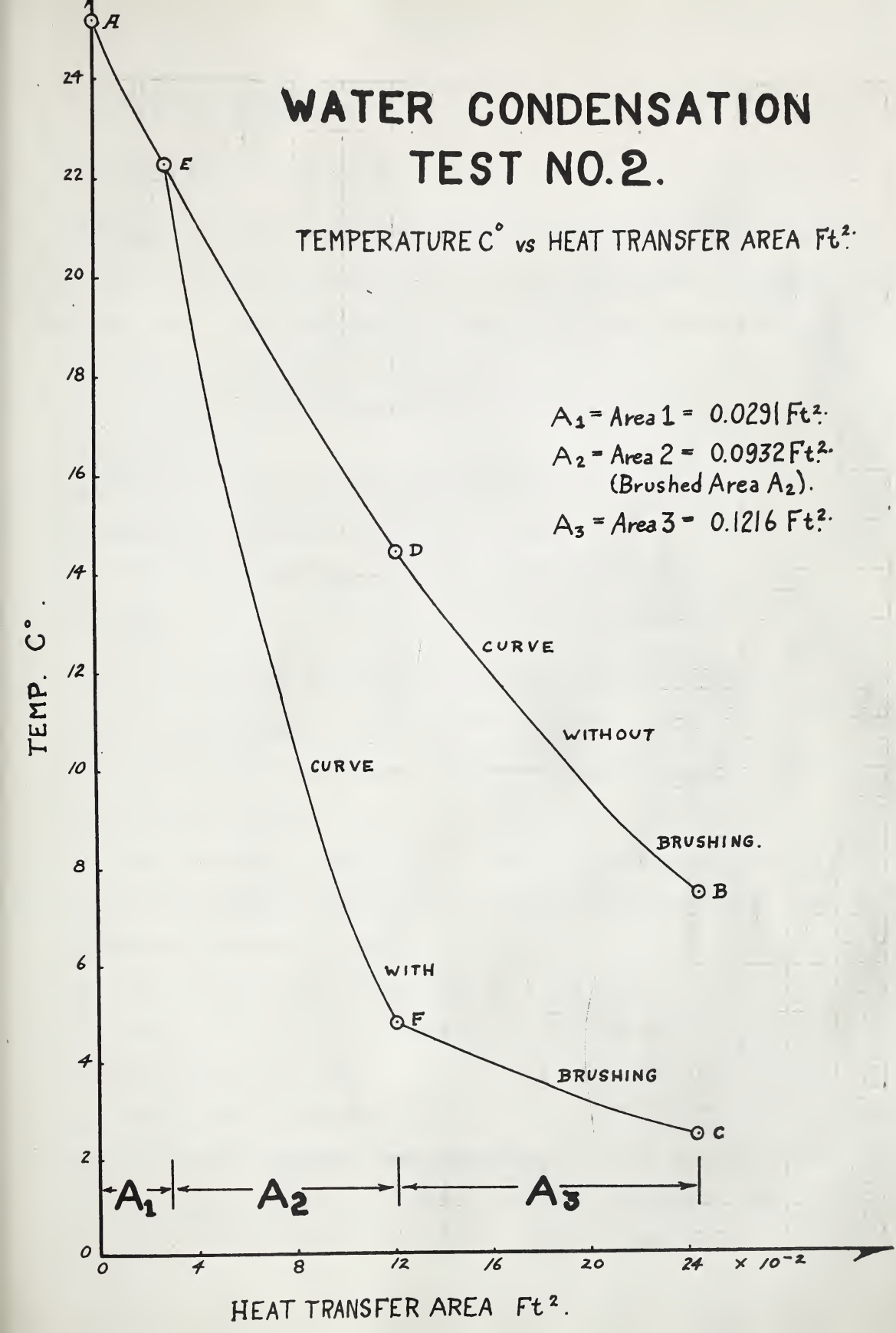
Since the heat transfer doefficient in area 3 was assumed the same with and without brushing, then point "F" in Fig. 9. could be located by the ratio method.

$$\frac{\Delta F}{\Delta C} = \frac{\Delta D}{\Delta B}$$

FIG. NO. 9

TEMPERATURE VS. HEAT TRANSFER AREA

WATER CONDENSATION TESTS


WATER CONDENSATION
TEST NO. 2.
TEMPERATURE C° vs HEAT TRANSFER AREA Ft².
A₁ = Area 1 = 0.0291 Ft².
A₂ = Area 2 = 0.0932 Ft².
(Brushed Area A₂).
A₃ = Area 3 = 0.1216 Ft².
A
E
D
B
F
C
CURVE WITHOUT BRUSHING.
CURVE WITH BRUSHING
A₁
A₂
A₃
TEMP. C°.
HEAT TRANSFER AREA Ft².
0
2
4
6
8
10
12
14
16
18
20
22
24
0
4
8
12
16
20
24
× 10⁻²

Therefore $\Delta F = \frac{\Delta C \times \Delta D}{\Delta B}$

$\Delta F = \frac{2.5 \times 14.5}{7.5} = 4.83$ or 4.8

The total heat transferred with brushing was calculated in a similar method to the previous, involving only a different terminal temperature, a different latent heat, and in some cases, an adjustment in the average specific heat.

(1) Sensible Heat.

$Q_s = 1.262 \times 0.248 (25.2 - 2.5) \times 1.8 = 12.8$ B.T.U. per hour.

(2) Latent Heat.

$Q_l = 1.262 \times 1073.2 \times (0.0196 - 0.0049) = 19.9$ B.T.U. per hour.

Q Total = 12.8 plus 19.9 = 32.7 B.T.U. per hour.

The heat transfer coefficient for the brushed surface is

$$U = \frac{Q_2}{A_2 \Delta m_2}$$

Where Q_2 was the heat transferred across area 2 in B.T.U. per hour

A_2 was the heat transfer area which is brushed, i.e. area 2.

Δm_2 was the log mean temperature difference between "E" and "F" in Fig.9 .

Now $Q_2 = Qt - (Q_1 + Q_3)$

i.e. The Heat transferred in area 2 (Q_2) is equal to the total heat transferred (Q_t) with brushing minus the total heat transferred in area 1 (Q_1) and 3 (Q_3)

Q_1 the heat transferred in area 1.

$Q_1 = 4.22 \times 0.0291 \times 23.5 \times 1.8 = 4.92$ B.T.U. per hour.

Similarly $Q_3 = 4.22 \times 0.1216 \times 3.5 \times 1.8 = 3.06$ B.T.U. per hour.

Therefore $Q_2 = Q_t - Q_1 - Q_3$

$Q_2 = 32.7 - 4.92 - 3.06 = 24.7$

∴ The heat transfer coefficient with brushing was

$$U = \frac{24.7}{0.0932 \times 11.5 \times 1.8} = 12.8 \text{ B.T.U. per hour. square feet, degrees F.}$$

The resistance of the water film removed by brushing was obtained from the relation

$$\frac{1}{h_d} = \frac{1}{U_d} - \frac{1}{U_c}$$ as predicted in the theory.

Where U_d is the heat transfer coefficient without brushing,

U_c is the heat transfer coefficient with brushing.

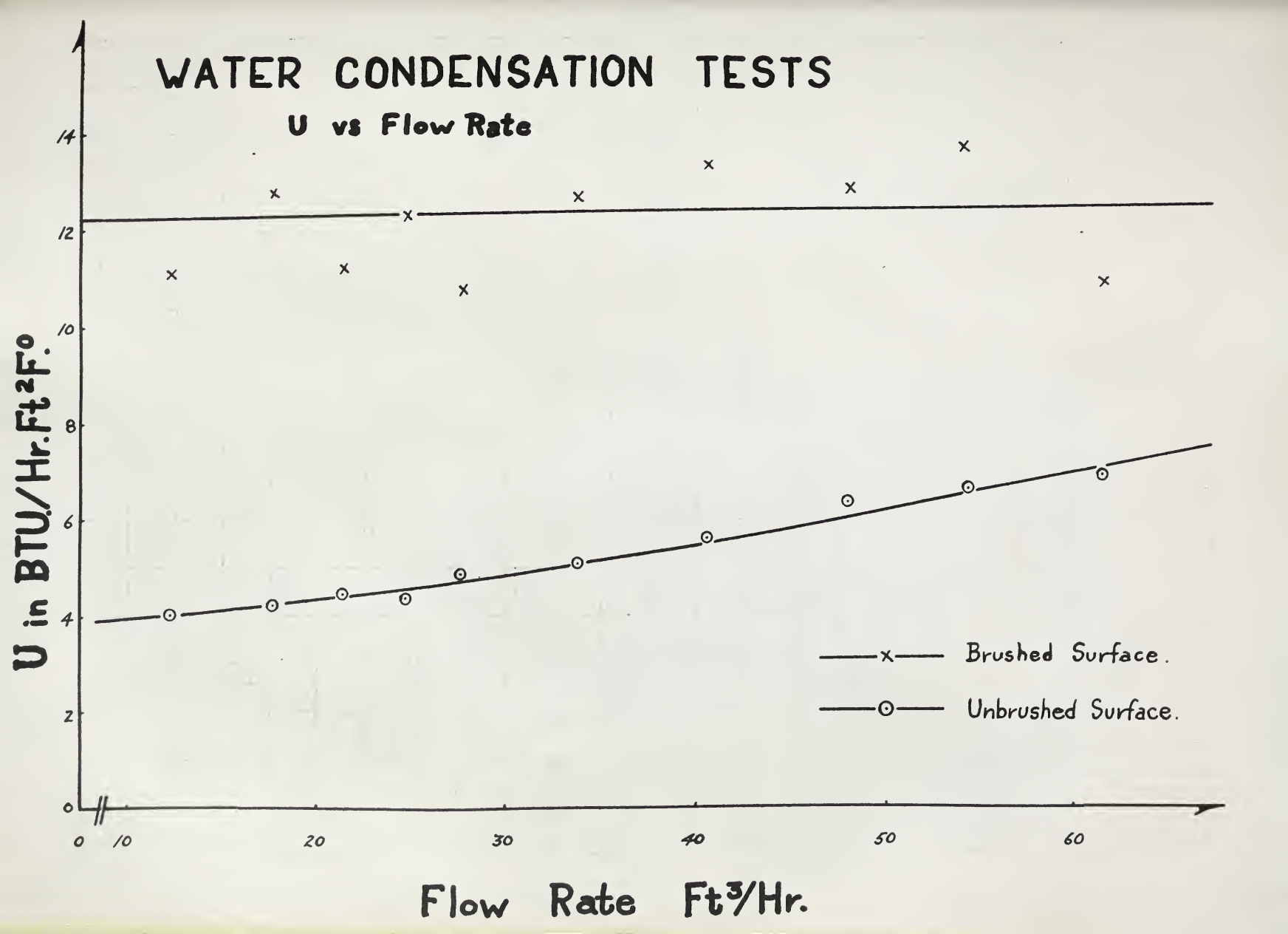
Therefore $\frac{1}{h_d} = \left(\frac{1}{4.22} - \frac{1}{12.8}\right)$

h_d = 6.50 B.T.U. per hour. square feet, degrees F.

FIG. NO. 10

HEAT TRANSFER COEFFICIENT U BRUSHED AND UNBRUSHED

VS. FLOW RATE Ft.3/Hr. WATER CONDENSATION TESTS


WATER CONDENSATION TESTS
U vs Flow Rate
U in BTU/Hr.Ft²F°
Flow Rate Ft³/Hr.
0
2
4
6
8
10
12
14
0
10
20
30
40
50
60
Brushed Surface.
Unbrushed Surface.

PART 11

THE REMOVAL OF A SOLID FROM A GAS PHASE

EXPERIMENTAL PROCEDURE

THE REMOVAL OF A SOLID FROM A GAS PHASE.

In these tests gaseous mixtures of carbon dioxide and dry air were used. The compositions used varied from ten to twenty mol percent carbon dioxide so as to resemble common industrial flue gases.

Ref. Fig.1.

The various gas mixtures were obtained by mixing high pressure (100 psig. air) "A" from valve "L" with carbon dioxide in the pressure cylinder "B". The carbon dioxide used was obtained from the cylinder "C" through the pressure reducing valve "5". Gas pressures in cylinder "B" were measured with a Bourdon type pressure gauge on a 6" deal. Also shown in Fig.1 is the gas holder "E" which was used to measure and mix the gas at low flow rates.

During the run, valves 3, 6, 7, 8, 9, 14, 15, 16, 19, 20 were open and valves 1, 2, 4, 5, 10, 11, 12, 13, 17, 18 were closed. Valve "8" was used as the control valve to adjust the flow.

The mixed gas flowed from the pressure cylinder "B" through valves 3, 6, 7, 8, 9, 14, through the gas meter "G", through the sulfuric acid dryer "H" where most of the moisture was removed, through the phosphorus pentoxide-glass wool packed tube dryer "I" where any traces of moisture still remaining were removed, then through the orifice meter "K" where the drygas volume was measured. The gas then entered the pyrex heat exchanger "M".

The heat exchanger was immersed to a definite height in the pyrex vacuum bottle "L". This bottle was filled with liquid oxygen or liquid air, depending upon which was available. The gas upon entering the heat exchanger was cooled down and the carbon dioxide snow precipitated on the heat transfer walls of the apparatus.

During the run the object of the rotating brush was to scrape off the carbon dioxide snow as formed on the inside walls of the pyrex heat exchanger and in this way decrease the resistance to heat flow and increase the heat transfer coefficient.

The snow then fell to the bottom of the heat exchanger.

The cold gas then passed around the copper-constantan thermocouple "d" and out into the atmosphere.

For an individual run the experimental procedure consisted of first obtaining the desired gas composition in pressure cylinder "B", by observing atmospheric pressure, closing valve "7" and allowing gas to flow from carbon dioxide cylinder "C" to a predetermined gauge pressure on cylinder "B", then closing valves 4, 5, and allowing high pressure air from "A" to flow into "B" to a predetermined final pressure. Valves 1 and 2 were then closed, valve "7" opened and the flow rate regulated by valve "8" to a definite manometer differential as measured at "K". The pinch cock valve "9" was then closed. Valve "10" was opened and air was passed through the heat exchanger "M" until all the moisture as well as any carbon dioxide from previous runs was flushed out. Valve "10" was then shut off, the outlet of the heat exchanger corked, and the heat exchanger carefully immersed in the liquid air to a predetermined depth. Any adjustment necessary was made by adding liquid air from another vacuum flask.

In the tests where the surface was brushed the motor was started before the heat exchanger was immersed.

The bath temperature as well as the outlet gas was measured by the thermocouple "d".

The cork at the outlet was removed, then simultaneous with the starting of the of the stop watch the pinch-cock "9" was released.

During the course of the run simultaneous measurements were taken of time and millivolt readings.

Tests were run with and without brushing at different gas velocities and different mol ratios.

SAMPLE CALCULATION

CARBON DIOXIDE - SUBLIMATION TESTS.

The data of outlet gas temperature in degrees centigrade and the time after commencement in seconds was computed for each individual run, as is shown in Table 2. These results were then plotted as outlet temperature v.s. time as is shown in Fig.11. for run numbers 523 and 623. A definite time (200 seconds after the commencement of the run) was chosen, and all the results were compared at this time. Two hundred seconds was chosen because it was a long enough period to achieve stable operating conditions and at the same time a short enough period so that the apparatus did not become plugged with carbon dioxide snow. If the run was continued too long, plugging caused a fluctuation resulting in a decrease in the flow rate.

As an example of the method of calculation used throughout, consider run numbers 523 and 623, Table number 3, and Fig.12.

The temperature of the outlet gas for the unbrushed case (run #623) was - 137.5 degrees Centigrade.

The temperature of the outlet gas for the brushed case (run #523) was - 172.0 degrees Centigrade.

The flow rate was 17.7 cubic feet per hour, measured at inlet gas temperature 21.0 degrees centigrade and one atmosphere pressure.

The composition of the gas mixture was calculated from the absolute pressures, assuming the ideal gas law to hold at these low pressures.

e.g. Barometric Pressure Reading was 701.7 mm. mercury.

this is equal to $701.7 \times \frac{14.69}{760} = 13.6$ psi

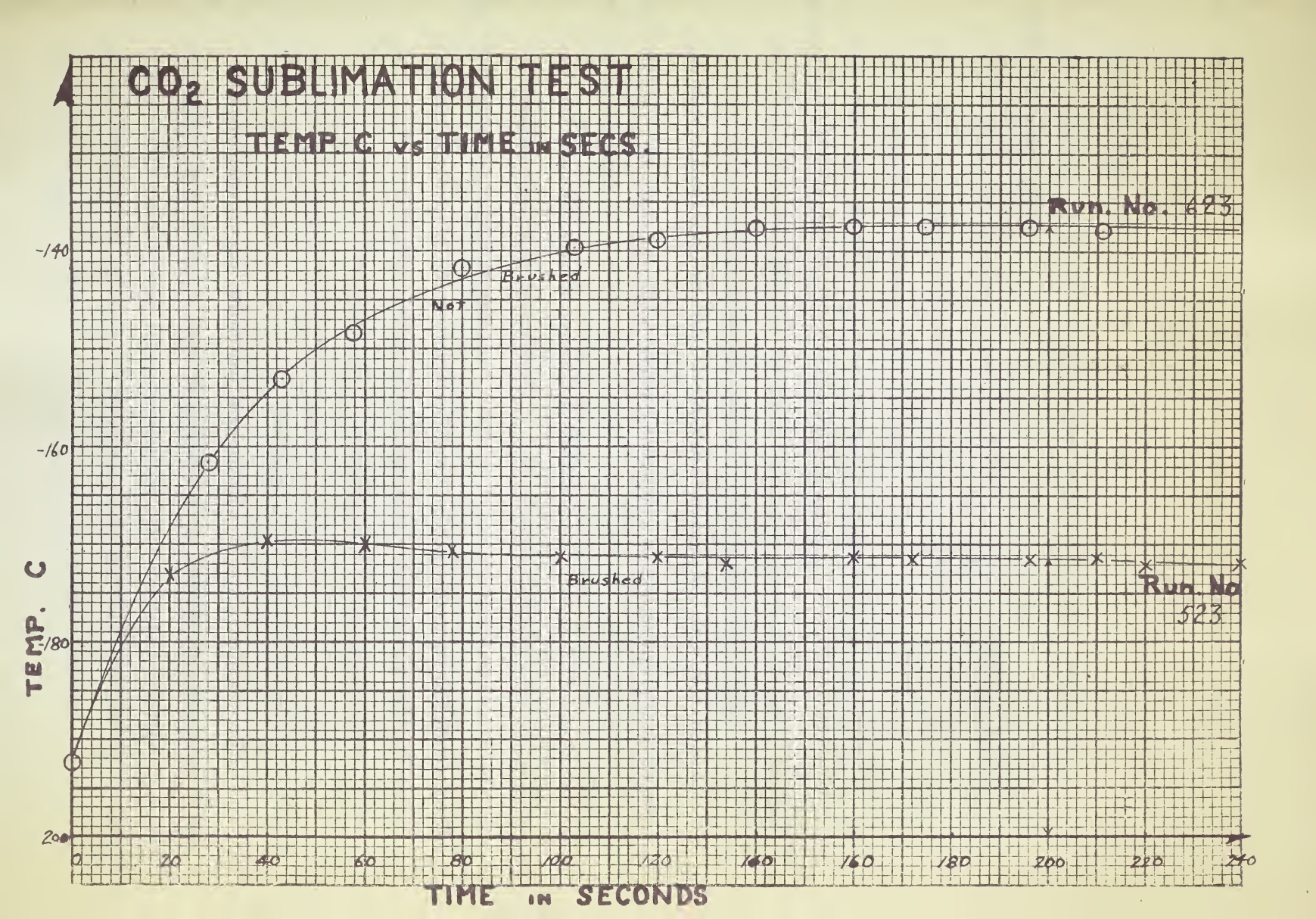
5.5 p sig of carbon dioxide was admitted from its cylinder to the pressure tank.

The high pressure air was then admitted until the total pressure in the tank reached a final 100.8 psig. (a certain period was allowed for cooling to room

FIG. NO. 11

TEMPERATURE VS. TIME

CARBON DIOXIDE SUBLIMATION TESTS


CO_2 SUBLIMATION TEST
TEMP. C vs TIME in SECS.
Run. No. 623
Not Brushed
Brushed
Run. No 523
-140
-160
-180
-200
TEMP. C
0
20
40
60
80
100
120
140
160
180
200
220
240
TIME IN SECONDS

temperature after the heating, due to the increase in pressure)

The percent carbon dioxide was then

$$\left(\frac{5.5}{(100.8 + 13.6)}\right) 100 = 4.83$$

Density of dry air at 21.0 degrees centigrade and 760 m.m. mercury is 0.0750 pounds per cubic foot.

Volume of dry carbon dioxide per hour is $17.7 \times \frac{4.83}{100} = 0.855$ cubic feet.

Therefore the number of pounds of dry air per hour is

$(17.70 - 0.855) \times 0.0750 = 1.267$ pounds.

Similarly, the density of dry carbon dioxide under the same conditions of temperature and pressure was 0.111 pounds per cubic foot.

Therefore, there was $0.855 \times 0.111 = 0.095$ pounds per hour of carbon dioxide.

Consider first the run where the surface is not brushed (run #623).

The heat removed from the gas to lower its temperature from 21.0 degrees centigrade at the inlet to -137.5 degrees centigrade at the outlet may be broken into two main parts:

(1) The heat given up by the carbon dioxide.

(2) The heat given up by the air.

(1) Heat from the Carbon Dioxide.

The heat given up by the carbon dioxide may again be divided into three parts.

(a) Q_1 The heat given out by cooling the carbon dioxide from the inlet gas temperature to the solidification temperature - 78.5 degrees centigrade.

(b) Q_L The latent heat of sublimation.

(c) Q_2 The heat required to cool the solid carbon dioxide from -78.5 degrees centigrade to the outlet gas temperature.

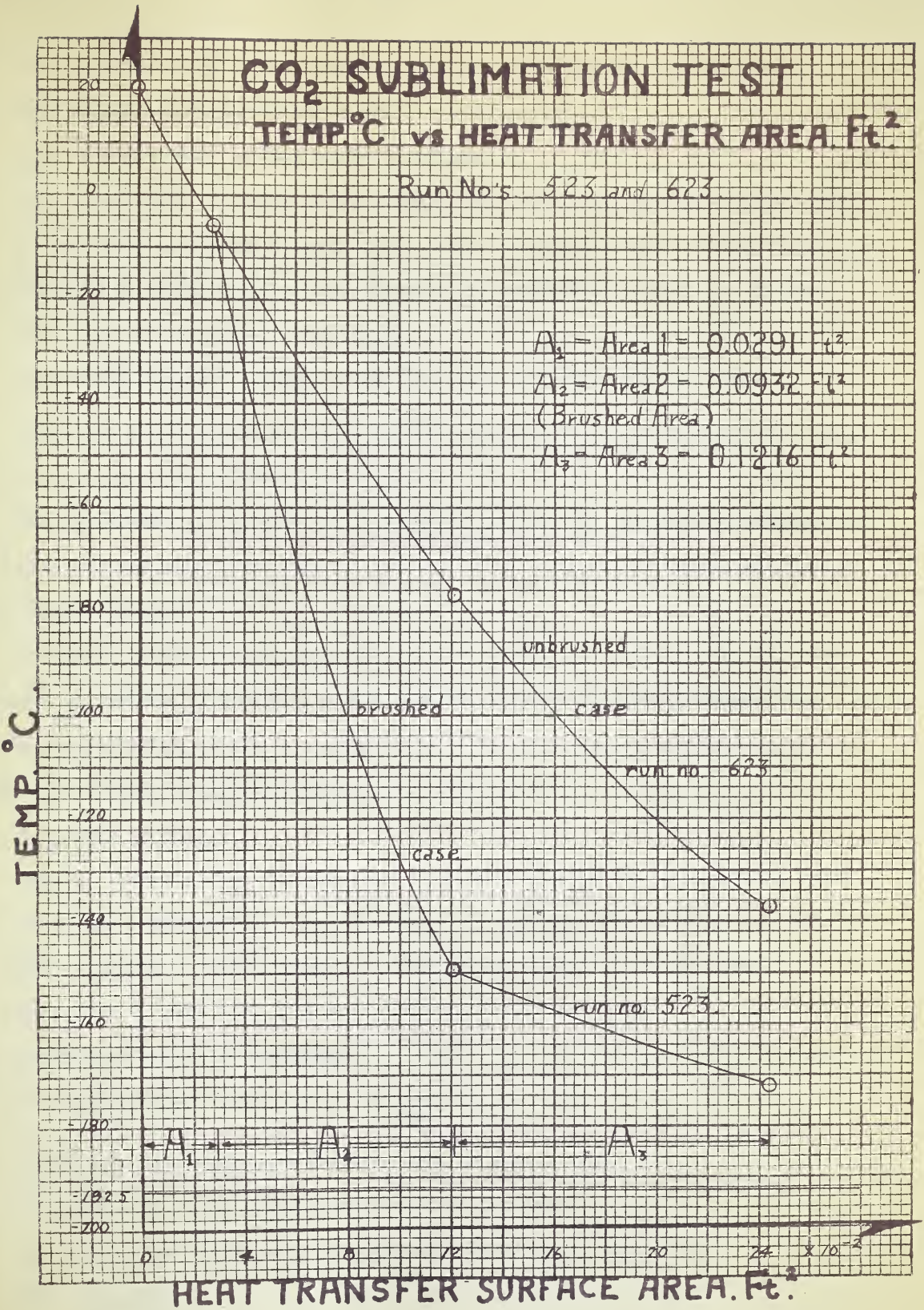
(a) Q_1 = Pounds of carbon dioxide per hour X the average specific heat of the carbon dioxide gas between inlet temperature (21.0 degrees centigrade) and the chosen sublimation temperature (-78.5 degrees centigrade X the temperature change).

$$Q_1 = 0.095 \times \frac{8.55}{44} \times (21.0 - -78.5) \times 1.8 = 3.31 \text{ B.T.U. per hour}$$

FIG. NO. 12

TEMPERATURE VS. HEAT TRANSFER AREA

CARBON DIOXIDE SUBLIMATION TESTS


CO_2 SUBLIMATION TEST
TEMP. °C vs HEAT TRANSFER AREA. Ft.²
Run No's 523 and 623
A_1 = Area 1 = 0.0291 ft²
A_2 = Area 2 = 0.0932 ft²
(Brushed Area)
A_3 = Area 3 = 0.1216 ft²
unbrushed case
run no. 623
brushed case
run no. 523
A_1
A_2
A_3
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-192.5
-200
TEMP. °C.
0
4
8
12
16
20
24
x 10⁻²
HEAT TRANSFER SURFACE AREA. Ft.²

(b) Q_L = Pounds of carbon dioxide per hour X the heat of sublimation (at -78.5 degrees centigrade) per pound.

Q_1 = 0.095 X 246.4 = 23.4 B.T.U. per hour.

(c) Q_2 = Pounds of solid carbon dioxide per hour X the average specific heat of the solid per pound between -78.5 degrees centigrade and the outlet gas temperature of -137.5 degrees centigrade X the temperature difference between -78.5 and -137.5 degrees centigrade.

$Q_2 = 0.095 \times \frac{12.5}{44} \times (-78.5 - -137.5) \times 1.8 \doteq 3.62$ B.T.U. per hour.

Therefore the total heat removed by the carbon dioxide is 3.31 plus 23.4 plus 3.62, which equals 30.33 B.T.U. per hour.

The values for the specific heats (gas and solid) and the heat of sublimation of carbon dioxide were obtained from the book "Carbon Dioxide by Quinn and Jones" (ref. Author index).

The above method of calculation checked to within one percent with the value obtained by the use of the "Solid-Liquid-Vapor Temperature-Entropy Diagram for Carbon Dioxide of Plank and Kuprionoff" and found in "Chemical Engineering Thermodynamics by Dodge" (see Dodge under Author index).

(2) Heat from the Air.

Qair = Pounds of dry air per hour X the average specific heat between inlet and outlet gas temperatures X the temperature difference between inlet and outlet.

Qair = 1.267 X 0.24 X (21.0 - - 137.5) X 1.8 = 86.8 B.T.U. per hour.

Therefore Q total = 30.33 + 86.8 = 117.13 B.T.U. per hour.

Q 623 = 117.1 B.T.U. per hour.

The heat transfer coefficient $U = \frac{Q}{A \triangle m}$

Where A is the total heat transfer area in square feet,

Q is the total heat transferred as B.T.U. per hour.

$\triangle m$ is the logarithmic mean temperature difference in degrees F.

$$\triangle m = \frac{\triangle_2 - \triangle_1}{\text{ln.} \frac{\triangle 2}{\triangle 1}}$$

Δ_2 = heat transfer driving force at the warm (inlet end) of the pyrex heat exchanger = 21.0 - - 192.5 = 213.5 degrees centigrade.

Δ_1 = heat transfer driving force at the outlet = -137.5 - - 192.5 = 55 degrees centigrade.

Therefore $\Delta m = \frac{213.5 - 55}{2.303 \log \frac{213.5}{55}}$ = 115.5 degrees centigrade.

Therefore $U = \frac{117.1}{0.2438 \times 115.5 \times 1.8}$ = 2.3 B.T.U. per hour, square ft. degrees F.

U Not Brushed = 2.3

Now consider Fig.12. "A" is the inlet temperature, "B" the outlet temperature. "D" is the log. mean temperature difference between "A" and "B". In a similar fashion, the log. mean between "A" and "D" and "D" and "B" were found. Continuing this process, the entire heat transfer curve between "A" and "B" was drawn. This is the heat transfer curve without brushing.

Consider the run where the surface is brushed, Run No. 523. Point "E" was located by the intersection between "A_1" and "A_2" and a vertical projection to the heat transfer curve. Since the heat transfer coefficient in "A_3" was assumed the same with or without brushing, then point "F" could be located by the ratio method.

$$\frac{\Delta F}{\Delta D} = \frac{\Delta C}{\Delta B}$$

Therefore $\Delta F = \frac{\Delta D \times \Delta C}{\Delta B} = \frac{115.5 \times (-172 - - 192.5)}{(-137.5 - - 192.5)}$

ΔF = 43.2

Therefore F = -192.5 plus 43.2 = -149.3 degrees Centigrade.

By using the log. mean temperature difference the curves E - F and F - C were drawn.

The heat transfer across "A_2" was calculated in a similar way to that shown for the total area without brushing. The only difference between the two calculations was in the terminal temperatures. The former terminal temperatures being "A" and "B", the latter "E" and "F". In some cases an adjustment was made to the specific

heats and the latent heats.

(1) Heat Lost by Carbon Dioxide.

$Q_1 = 0.095 \times \frac{8.55}{44} \times (-5.5 - -78.5) \times 1.8 = 2.42$ B.T.U. per hour

$Q_L = 0.095 \times 246.4 = 23.4$ B.T.U. per hour.

$Q_2 = 0.095 \times \frac{12.5}{44} \times (-78.5 - -149.3) \times 1.8 = 3.44$ B.T.U. per hour.

Q carbon dioxide = 2.42 plus 23.4 plus 3.44 = 29.26 B.T.U. per hour.

(2) Q air = $1.267 \times 0.24 \times (-5.5 - -149.3) \times 1.8 = 78.5$ B.T.U. per hour.

Q total for area 2 with brushing = 29.26 plus 78.5 = 107.8 B.T.U. per hour.

Δm was found in a similar fashion.

Therefore $U = \frac{Qt}{A_2 \times m} = \frac{107.8}{0.0932 \times 97.6 \times 1.8} = 6.45$

The heat transfer coefficient with brushing is 6.45 B.T.U. per hour, square feet, degrees F.

The resistance of the carbon dioxide snow deposit removed by brushing was obtained from the relation

$\frac{1}{h_d} = \frac{1}{U_d} - \frac{1}{U_c}$ as predicted in the theory.

Where U_d is the heat transfer coefficient without brushing,

U_c is the heat transfer coefficient with brushing.

Therefore $\frac{1}{h_d} = (\frac{1}{2.3} - \frac{1}{6.45}) = 0.272$

$\therefore$ $h_d = 3.67$ B.T.U./Hr. Ft. $^{\circ}$F.

FIG. NO. 13

HEAT TRANSFER COEFFICIENT U BRUSHED AND UNBRUSHED

VS. FLOW RATE Ft.^{3}/Hr. CARBON DIOXIDE SUBLIMATION TESTS

FIG. 13.

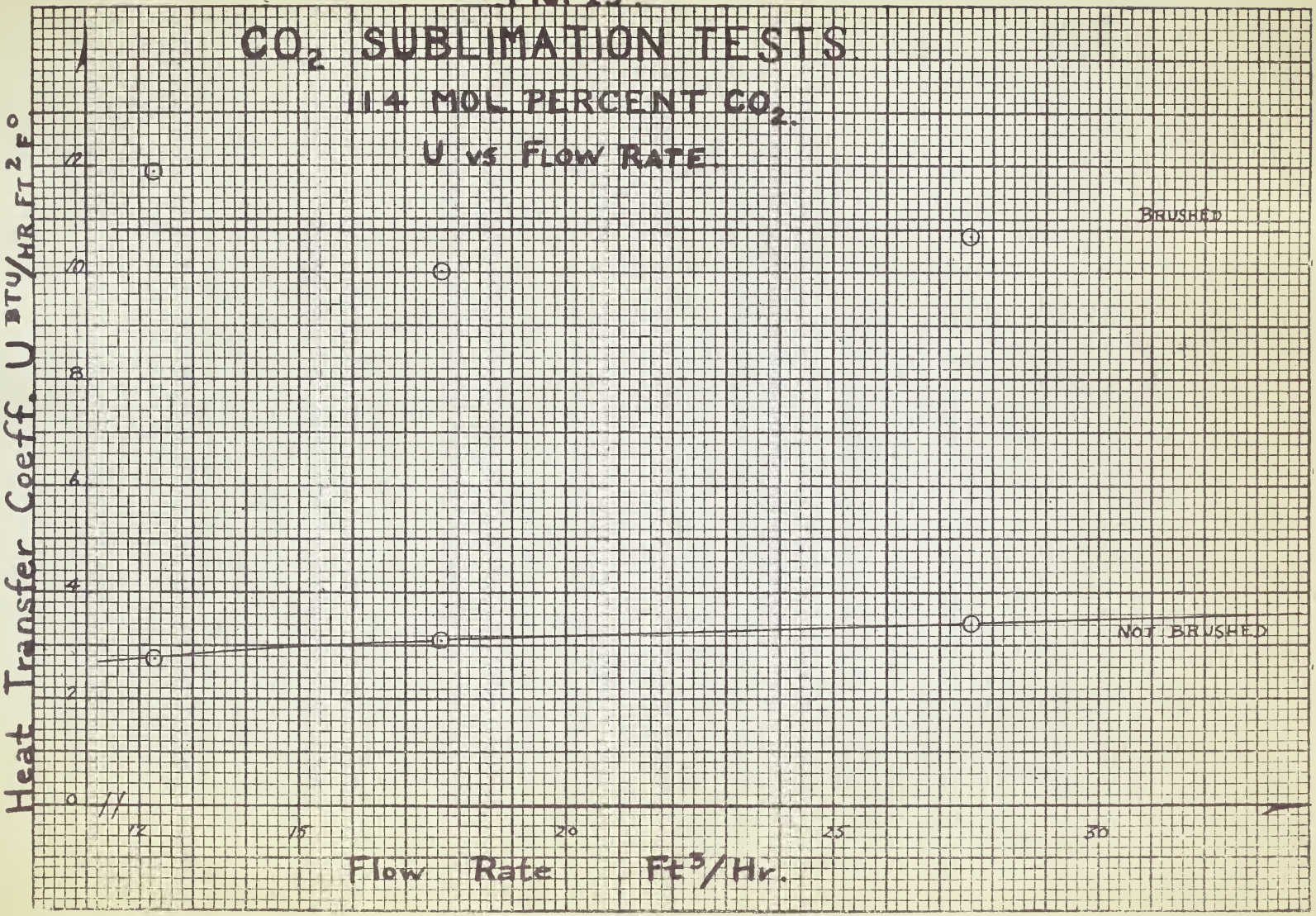

CO2 SUBLIMATION TESTS
11.4 MOL PERCENT CO2.
U vs Flow Rate.
Heat Transfer Coeff. U BTU/HR.FT2F°
BRUSHED
NOT BRUSHED
0
2
4
8
10
12
15
20
25
30
Flow Rate Ft3/Hr.

FIG. NO. 14

CARBON DIOXIDE THERMODYNAMIC DIAGRAM

(See back cover)

DISCUSSION OF EXPERIMENTAL RESULTS

DISCUSSION OF EXPERIMENTAL RESULTS

Condensation Tests

The water condensation tests (see Fig. 8) reveal that a plot of the temperature of the gas outlet versus flow rate results in smooth curves of increasing temperature with flow rate. Both curves (with brushing and without brushing) appear to level off and approach each other at higher flow rates.

In Fig. 9 the effect of brushing is clearly illustrated by the slopes of the lines temperature versus heat transfer area. The curve A-D-B without brushing is seen to slope down at an angle of about forty-five degrees resulting in the terminal (outlet) temperature at B. However the curve with brushing A-E-F-C results in a lower terminal (outlet) temperature at C. The curve for the brushed area A_2 is seen to be very steep sloping at an angle of about eighty degrees. It is also observed that almost all the temperature change, consquently almost all of the heat transfer (with brushing) occurs over the brushed area A_2.

The results illustrated in Figs. 8 and 9 for run number 2 are general for all the liquid condensation tests.

In Fig. 10 the values for the heat transfer coefficient with and without brushing are plotted against their respective flow rates for all the water condensation tests. The curve for the unbrushed conditions appears to be quite smooth and the value for U increases with increasing flow rate. The values for U versus flow rate with brushing however do not result in a single smooth curve but result in a series of points dispersed along a line. This dispersion is due to a large variance in the effectiveness of the brushing. The effect of brushing as might be expected is not consistant, and is controlled by a large number of independant variables. The heat transfer

coefficient U (with brushing) appears to be almost independant of flow rate, increasing slightly with the flow rate. The U for brushing appears to vary between limits depending on the effectiveness of brushing.

In table 1. values of h_d are also listed. h_d is the conductivity of the deposit removed by brushing expressed in B.T.U.'s per hour square feet degree fahrenheit. $1/h_d$ is then the resistance offered by the deposit which was removed. The values of $1/h_d$ would decrease with the flow rate. It is then apparent that the increased heat transfer due to the brushing is more effective at lower flow rates than higher, since a larger resistance to heat flow is removed by brushing at a low flow rate than at a high one.

Sublimation Tests

The plot of the temperature of the gas outlet versus time for the brushed and unbrushed conditions illustrated by Fig. 11 resulted in smooth curves increasing in temperature with time. The curves rising sharply at the start are observed to level off as equilibrum is attained at constant flow rate. The time lag in the thermocouple was too small to introduce any appreciable error. However an error did exist in the "simultaneous" readings of time and temperature and another error in the graphical solution. The inconsistancies of brushing were sufficiently great so that no effective analyses of errors could be carried out. It will be noted that there is a characteristic "hump" in the temperature versus time curve near the start for the brushed condition. The decrease in temperature after the "hump" is probably due to a build up of hard carbon dioxide snow around the tips of the bristles in the brush thus increasing the scraping effect and contributing to the brushing efficiency.

The heat transfer coefficient U was plotted against flow rate for each composition. This plot is illustrated by Fig. 13 for 11.4 mol. percent carbon

dioxide. The results for these tests were similar to the corresponding plot for the liquid condensation tests illustrated by Fig. 10. and the same conclusions apply. The curve for the not brushed condition is quite smooth and the heat transfer coefficient U increases with the flow rate. The curve of U versus flow rate for the brushed condition appears to be independant of flow rate. Again there is the dispersion of points for the brushed condition due to variations in mechanical brushing action.

The Effect of Mol Percent Carbon Dioxide on U

The heat transfer coefficient U (both for the brushed and unbrushed condition) increases with increasing percentage of carbon dioxide in the inlet gas. Tests were made at 4.83 percent carbon dioxide and 39.5 percent carbon dioxide to show the effect of composition. The heat transfer coefficients (see table 3) without brushing were respectively 2.30 and 4.51, the heat transfer coefficients with brushing were 6.45 and 16.7 respectively.

CONCLUSION

CONCLUSION

It is concluded that the heat transfer can be increased by brushing two to five times that without brushing.

The highest heat transfer coefficient obtained in the tests was 16.7 B.T.U.'s per hour square feet degrees fahrenheit. This heat transfer was obtained with 39.5 mol. percent carbon dioxide and a flow rate of 17.7 cubic feet per hour with brushing. The lowest heat transfer was 2.30 B.T.U.'s per hour feet squared degrees fahrenheit. This heat transfer was obtained with 4.83 mol. percent carbon dioxide and a flow rate of 17.7 cubic feet per hour without brushing.

It is suggested that further development include an investigation of the effect of brushing speed as well as a study of other methods for removing the surface film.

TABLES

TABLE NO. 1

WATER CONDENSATION TESTS

Conditions.

Each run is an average of three separate tests.
Motor speed held constant between 825 and 850 rpm.
Temperature of ice and water bath is zero degrees centigrade.

Run No.	Conditions of Heat Transfer Surface, brushed or not brushed	Flow Rate $Ft^3/Hr.$ At 1 Atm.	Inlet Temp. °C.	Outlet Temp. ° C.	Humidity Absolute lbs.H_2O/lb. of Dry Air Inlet	Outlet	Heat Transfer Coeff. U BTU/ $Hr.Ft^{2o}F.$	Conductivity Coeff. of Film Removed h_d $BTU/HrFt^{2o}F.$
1.	brushed	12.35	25.2	1.0	0.0184	0.0046	11.1	6.33
	not brushed	12.35	25.2	4.7	0.0184	0.0055	4.03	
2.	brushed	17.70	25.2	2.5	0.0196	0.0049	12.8	6.50
	not brushed	17.70	25.2	7.5	0.0196	0.0071	4.22	
3.	brushed	21.38	25.2	4.0	0.0201	0.0054	11.2	7.52
	not brushed	21.38	25.2	9.0	0.0201	0.0079	4.50	
4.	brushed	24.85	25.5	5.3	0.0201	0.0060	12.7	6.67
	not brushed	24.85	25.5	10.2	0.0201	0.0087	4.36	
5.	brushed	27.62	25.7	6.5	0.0201	0.0065	10.7	9.17
	not brushed	27.62	25.7	10.7	0.0201	0.0089	4.94	
6.	brushed	33.8	25.7	7.7	0.0201	0.0071	12.7	8.70
	not brushed	33.8	25.7	12.3	010201	0.0098	5.16	
7.	brushed	40.7	25.8	9.0	0.0201	0.0076	13.4	10.20
	not brushed	40.7	25.8	12.9	0.0201	0.0101	5.74	
8.	brushed	48.1	25.8	10.0	0.0201	0.0085	12.9	12.83
	not brushed	48.1	25.8	13.5	0.0201	0.0106	6.41	
9.	brushed	54.3	25.8	10.2	0.0196	0.0087	13.8	15.15
	not brushed	54.3	25.8	13.3	0.0196	0.0103	7.22	
10.	brushed	61.7	25.9	11.5	0.0185	0.0092	10.9	18.90
	not brushed	61.7	26.0	14.5	0.0185	0.0109	6.88	

TABLE NO. 2

CARBON DIOXIDE SUBLIMATION TESTS

DATA FOR CURVES: Outlet Gas Temperature vs. Time from Start of Run.

Composition = 4.83% CO_2
Rate = 17.7 Cu. ft. per Hour

Composition = 4.83% CO_2
Rate = 17.7 Cu. ft. per Hour

RUN NO.	223	323		623		523	
	Not Brushed	Brushed		Not Brushed		Brushed	
Time Secs.	Outlet Temp. °C.	Time Secs.	Outlet Temp. °C.	Time Secs.	Outlet Temp. °C.	Time Secs.	Outlet Temp. °C.
0	-192.5	0	-192.5	0	-192.5	0	-197.5
10	-164.5	15	-171.2	28	-161.5	20	-173.0
28	-134.5	30	-170.5	43	-153.0	40	-169.5
50	-144.5	47	-172.0	58	-148.5	60	-170.0
80	-141.5	60	-172.0	80	-141.5	78	-170.5
131	-141.5	75	-173.0	103	-139.5	100	-171.2
151	-143.0	120	-174.0	120	-139.0	120	-171.2
177	-138.7	145	-173.5	142	-137.5	134	-172.0
195	-139.0	162	-173.0	160	-137.5	160	-171.0
221	-138.0	185	-173.5	175	-137.5	172	-171.5
245	-139.5	200	-173.0	196	-137.5	192	-171.5
267	-136.7	214	-173.0	211	-138.0	210	-171.0
		228	-172.0	229	-133.5	220	-172.0
				249	-134.0	240	-172.0

Composition = 11.4% CO_2
Flow Rate = 12.3 Cu. ft. per Hour

Composition = 11.4% CO_2
Flow Rate = 17.7 Cu. ft. per Hr.

RUN NO.	312	412		112		212	
	Not Brushed	Brushed		Not Brushed		Brushed	
0	-185.0	0	-185.0	0	-185.0	0	-185.0
10	-179.5	14	-173.0	22	-166.5	9	-174.0
30	-169.0	79	-174.0	40	-154.5	34	-169.2
41	-168.0	93	-176.8	68	-152.3	55	-168.0
65	-165.2	108	-180.0	82	-141.8	79	-168.0
80	-163.8	125	-180.1	97	-140.8	95	-169.0
95	-160.4	140	-181.0	124	-138.0	114	-169.0
108	-160.0	160	-181.0	138	-136.0	130	-170.0
126	-157.0	185	-182.5	160	-136.0	145	-170.0
163	-155.0	202	-182.5	171	-136.8	165	-170.0
185	-154.5	216	-182.5	194	-136.0	179	-170.0
200	-154.5	264	-182.5	218	-132.5	211	-170.0
223	-153.5	300	-182.5	230	-134.0	230	-173.0
253	-152.2			245	-133.5	258	-174.0

TABLE NO. 2 (Cont'd)

Composition = 11.4% CO_2
Flow Rate = 27.6 Cu. ft. per Hour

RUN NO.	512		612	
	Not Brushed		Brushed	
Time Secs.	Outlet Temp. °C.	Time Secs.	Outlet Temp. °C.	
0	-185.0	0	-185.0	
12	-132.5	15	-161.0	
32	-118.0	29	-151.0	
48	-113.0	41	-144.0	
59	-109.0	58	-145.0	
80	-108.4	70	-146.0	
100	-106.0	83	-147.0	
120	-105.5	114	-146.0	
137	-103.5	150	-146.0	
162	-102.5	175	-147.0	
201	-103.0	210	-147.0	
230	-103.0	240	-147.0	

Composition = 13.4% CO_2
Flow Rate = 12.3 Cu. ft. per Hour

RUN NO.	516		616	
	Not Brushed		Brushed	
0	-185.0	0	-185.0	
6	-184.0	7	-184.0	
20	-173.0	17	-174.0	
32	-161.5	32	-174.0	
46	-157.0	50	-173.0	
60	-151.0	68	-173.0	
72	-148.5	84	-174.0	
90	-147.0	101	-175.0	
104	-143.5	131	-176.0	
119	-146.0	152	-180.0	
156	-144.0	172	-174.0	
184	-138.7	186	-174.0	
197	-140.0	208	-173.0	
213	-139.5	225	-173.0	
230	-136.5	252	-172.0	

Composition = 13.4% CO_2
Flow Rate = 17.7 Cu. ft. per Hr.

	316		416	
	Not Brushed		Brushed	
0	-185.0	0	-185.0	
9	-174.0	4	-181.0	
22	-153.5	16	-165.0	
40	-146.5	26	-163.8	
50	-145.2	66	-163.8	
58	-144.0	80	-165.0	
76	-141.5	103	-164.5	
100	-139.5	117	-165.0	
117	-141.5	139	-161.5	
130	-139.5	153	-160.0	
145	-141.0	170	-158.0	
158	-134.5	182	-159.0	
173	-132.0	195	-160.0	
185	-128.0	206	-161.0	
202	-128.0	220	-159.0	
217	-128.0	240	-159.0	
234	-126.0			

TABLE NO. 2 (Cont'd)

Composition = 13.4% CO_2
Flow Rate = 27.6 Cu. ft. per Hour

RUN NO.	116		216					
	Not Brushed		Brushed		Not Brushed		Brushed	
Time Secs.	Outlet Temp. °C.		Time Secs.	Outlet Temp. °C.	Time Secs.	Outlet Temp. °C.	Time Secs.	Outlet Temp. °C.
0	-185.0		0	-185.0				
20	-129.0		17	-169.0				
34	-121.0		27	-160.0				
62	-120.0		43	-156.8				
78	-119.0		54	-157.5				
126	-113.5		68	-156.7				
148	-114.0		80	-157.5				
165	-112.8		102	-150.8				
185	-112.0		118	-153.5				
208	-111.5		138	-152.5				
227	-110.0		155	-150.0				
265	-109.5		185	-147.5				
			200	-146.0				
			220	-146.0				

Composition = 16.9% CO_2
Flow Rate = 12.3 Cu. ft. per Hour

Composition = 16.9% CO_2
Flow Rate = 17.7 Cu. ft. per Hour

RUN NO.	315		415		314		115	
	Not Brushed		Brushed		Not Brushed		Brushed	
0	-185.0	0	-185.0	0	-185.0	0	-185.0	
12	-173.0	19	-176.0	10	-164.0	12	-180.0	
24	-161.0	33	-176.0	30	-145.0	20	-169.0	
35	-158.0	45	-175.0	52	-126.0	36	-166.0	
54	-151.0	56	-173.0	66	-125.0	58	-164.0	
66	-148.0	73	-174.0	84	-124.0	78	-165.0	
80	-147.5	86	-174.0	100	-122.0	94	-165.0	
90	-144.0	100	-174.0	115	-121.0	112	-164.3	
106	-140.0	115	-174.0	141	-121.0	120	-163.0	
118	-138.0	132	-174.0	160	-121.0	160	-160.0	
132	-137.0	142	-173.0	182	-121.0	180	-157.0	
148	-137.0	158	-175.0	210	-121.5	190	-155.0	
165	-137.0	186	-174.0	251	-120.0	208	-158.0	
186	-137.5	200	-173.0	278	-118.5	240	-159.0	
202	-136.0	222	-173.0					
222	-136.0	250	-173.0					
240	-135.0							

TABLE NO. 2 (Cont'd)

Composition = 16.9% CO_2
Flow Rate = 27.6 Cu. ft. per Hour

RUN NO.	114	214	
	Not Brushed	Brushed	
Time Secs.	Outlet Temp. °C.	Time Secs.	Outlet Temp. °C.
0	-185.0	0	-185.0
34	-126.4	9	-182.5
45	-120.5	25	-153.2
65	-120.0	40	-150.0
78	-113.0	53	-143.2
97	-111.2	70	-143.2
116	-110.0	89	-144.0
132	-110.0	106	-144.0
144	-109.0	130	-146.0
177	-108.4	140	-148.0
200	-107.2	160	-146.0
217	-106.0	208	-145.0
240	-107.0	230	-145.0

Composition = 16.9% CO_2
Flow Rate = 32.2 Cu. ft. per Hr.

	415	515	
	Not Brushed	Brushed	
Time Secs.	Outlet Temp. °C.	Time Secs.	Outlet Temp. °C.
0	-185.0	0	-192.5
12	-130.5	18	-137.5
24	-114.5	32	-133.5
35	-109.0	38	-136.0
54	-106.5	67	-133.5
66	-104.0	95	-132.5
80	-103.5	108	-134.4
90	-102.0	122	-132.5
106	-102.0	135	-134.4
118	-102.0	163	-134.4
132	-102.0	180	-132.5
186	-103.0	199	-132.0
202	-101.0	224	-132.0
222	-101.0	234	-130.5
240	-101.0	260	-128.5

Composition = 39.5% CO_2
Flow Rate = 17.7 Cu. ft. per Hour

RUN NO.	123	222	
	Not Brushed	Brushed	
0	-192.5	0	-192.5
9	-185.0	8	-180.0
23	-127.5	15	-171.4
36	-128.5	32	-172.0
62	-121.0	50	-172.5
94	-113.5	70	-173.0
110	-112.8	90	-171.0
135	-111.0	105	-171.0
150	-111.0	120	-171.0
170	-111.0	140	-170.0
210	-109.5	173	-167.0
225	-107.0	211	-164.5
240	-108.0	238	-163.5
		250	-164.5

Composition = 39.5% CO_2
Flow Rate = 17.7 Cu. ft. per Hr.

	322	422	
	Not Brushed	Brushed	
0	-192.5	0	-192.5
6	-185.0	7	-184.5
20	-140.8	15	-169.0
32	-123.5	30	-166.5
53	-115.5	43	-164.5
70	-116.0	70	-166.5
113	-106.5	80	-164.5
135	-109.0	111	-164.0
150	-109.0	130	-164.0
175	-109.0	145	-164.0
207	-108.0	150	-164.0
233	-109.0	160	-164.0
		180	-164.0
		211	-164.0
		240	-163.0

TABLE NO. 3

CARBON DIOXIDE SUBLIMATION TESTS

Conditions of Test:

Readings at 200 seconds after start of Test.

Run No.	Mol. % Carbon Dioxide	Condition of Heat Transfer Surface, brushed or not brushed	Flow Rate $Ft^3/Hr.$ at 1 Atm.	Inlet Temp. °C.	Outlet Temp. °C.	Bath Temp. °C.	Heat Transfer Coeff. U BTU/ $Hr.Ft^{2o}F$	Conductivity Of Film Removed h_d $BTU/HrFt^{2o}F.$
223	4.83	not brushed	17.7	21.0	-137.5	-192.5	2.30	3.67
623	4.83	not brushed	17.7	21.0	-137.5	-192.5	2.30	
323	4.83	brushed	17.7	21.0	-172.0	-192.5	6.45	3.67
523	4.83	brushed	17.7	21.0	-172.0	-192.5	6.45	
312	11.4	not brushed	12.3	23.0	-154.5	-185.0	2.74	3.69
412	11.4	brushed	12.3	23.0	-182.5	-185.0	11.9	
112	11.4	not brushed	17.7	23.0	-134.0	-185.0	3.07	4.43
212	11.4	brushed	17.7	23.0	-170.0	-185.0	10.0	
512	11.4	not brushed	27.6	23.1	-103.0	-185.0	3.42	5.03
612	11.4	brushed	27.6	23.1	-147.0	-185.0	10.7	
516	13.4	not brushed	12.3	23.0	-139.0	-185.0	2.38	3.39
616	13.4	brushed	12.3	23.0	-173.5	-185.0	8.02	
316	13.4	not brushed	17.7	23.1	-126.0	-185.0	2.98	4.63
416	13.4	brushed	17.7	23.0	-159.0	-185.0	8.35	
116	13.4	not brushed	27.6	23.0	-110.5	-185.0	4.00	6.33
216	13.4	brushed	27.6	23.1	-146.0	-185.0	10.9	

TABLE NO. 3 (Cont'd)

Run No.	Mol. % Carbon Dioxide	Condition of Heat Transfer Surface, brushed or not brushed	Flow Rate $Ft^3/Hr.$ at 1 Atm.	Inlet Temp. °C.	Outlet Temp. °C.	Bath Temp. °C.	Heat Transfer Coeff. U BTU/ $Hr.Ft^{2o}F$	Conductivity Of Film Removed h_d $BTU/HrFt^{2o}F$
315	16.9	not brushed	12.3	22.0	-136.0	-185.0	2.56	3.56
415	16.9	brushed	12.3	22.0	-173.0	-185.0	9.07	
314	16.9	not brushed	17.7	25.0	-121.0	-185.0	3.18	4.78
115	16.9	brushed	17.7	25.0	-158.5	-185.0	9.50	
114	16.9	not brushed	27.6	25.1	-106.5	-185.0	4.35	6.42
214	16.9	brushed	27.6	25.1	-145.0	-185.0	13.5	
415	16.9	not brushed	32.2	25.0	-101.0	-185.0	4.75	7.52
515	16.9	brushed	32.2	25.0	-132.0	-185.0	13.0	
123	39.5	not brushed	17.7	22.5	-108.5	-192.5	4.51	6.17
322	39.5	not brushed	17.7	22.5	-108.5	-192.5	4.51	
222	39.5	brushed	17.7	22.5	-164.0	-192.5	16.7	6.17
422	39.5	brushed	17.7	22.5	-164.0	-192.5	16.7	

APPENDIX

APPENDIX

(A) AUTHOR INDEX

AUTHOR	TITLE	PUBLISHER	DATE	VOLUME	PAGE
Badger & McCabe	Elements of Chemical Engineering	McGraw-Hill	1936	2nd Addn.	134-155
Chemical Abstracts	American Chemical Society		1929	24	5894
			1931	25	1922
			1931	25	238
			1933	27	4321
			1934	28	4136
			1934	28	5552
			1934	28	1422
			1935	29	6970
Dodge	Chemical Engineering Thermodynamics	McGraw-Hill	1944	1st Addn.	662
Keyes & Deem	Chemical Engineer's Manual	Wiley	1942	1st Addn.	205
McAdams	Heat Transmission	McGraw-Hill	1942	2nd Addn.	--
Perry	Chemical Engineer's Handbook	McGraw-Hill	1941	2nd Addn.	--
Quinn & Jones	Carbon Dioxide	Reinhold Publishing	1936		78 70
Walker Lewis & McAdams & Gilliland	Principles of Chemical Engineering	McGraw-Hill	1937	3rd Addn.	720

P A T E N T S

PATENT NO.	DATE	AUTHOR
Brit. 330, 886 - 7	1929	C. V. Vogt
U.S. 1,791,772 - 3 - 4	1931	C. V. Vogt
U.S. 1,783,864 - 5 - 6 - 7	1931	C. V. Vogt
U.S. 1,915,634	1933	C. V. Vogt
U.S. 1,956,141	1934	C. V. Vogt
U.S. 1,965,618	1934	C. V. Vogt
U.S. 1,940,109	1934	C. V. Vogt
U.S. 2,013,016 - 17 - 18	1935	C. V. Vogt

SOLID-LIQUID-VAPOR

TEMPERATURE-ENTROPY DIAGRAM

FOR

CARBON DIOXIDE

TRANSPOSED FROM THE GERMAN DATA

OF

PLANK AND KUPRIANOFF

BY

F. B. HUNT

CHICAGO, ILL.

JAN. 8, 1930

Temp. in °F — P = lb. per sq. in., abs.

i = B.t.u. per lb. — V = cu. ft. per lb.

At critical point t = 87.8 °F.

P = 1066.3 lb. per sq. in.

Degrees

300 290 280 270 260 250 240 230 220 210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 32 30 20 10 ±0 -10 -20 -30 -40 -50

P=1700 lb. per sq. in. abs.

320 315 310 305 300 295 290 285 280 275 270 265 260 255 250 245 240 235 230 225 220 215 210 205 200 195 190 185 180 175 170 165 160 155 150 145 140 135

V=0.04 0.06 0.08 0.10 0.15 0.20

x=0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9

R

AGRAM

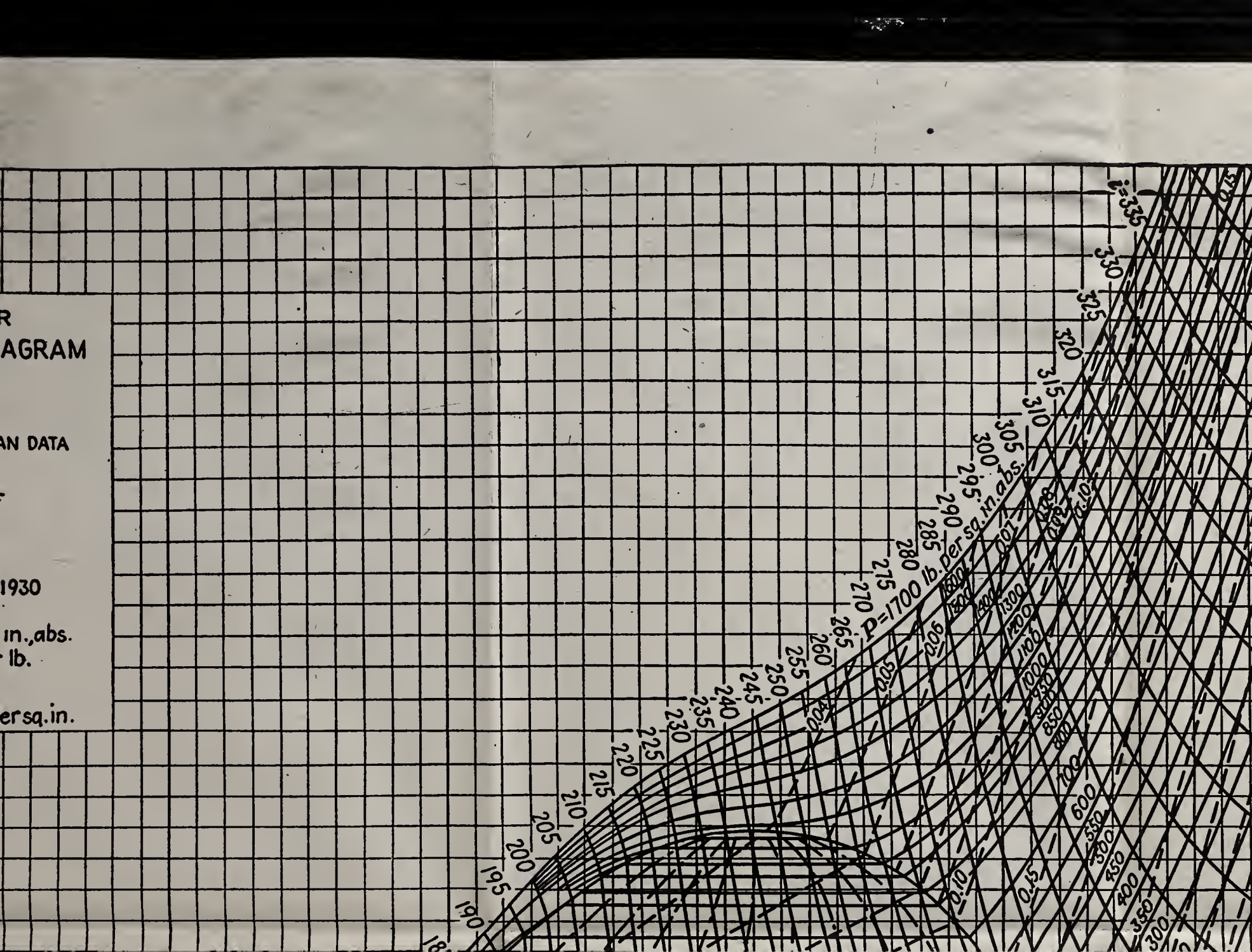
AN DATA

1930

in., abs.

lb.

ersq.in.



CHICAGO, ILL. JAN. 8, 1930

Temp. in °F — P = lb. per sq. in., abs.
i = B.t.u. per lb. — V = cu. ft. per lb.

At critical point t = 87.8 °F.
P = 1066.3 lb. per sq. in.

Degrees

S →

Solid-liquid-vapor–temperature-entropy diagram for carbon dioxide. Note that i is used for enthalpy in B.t.u. per pound. (*Courtesy of F. B. Hunt of the Liquid Carbonic Corporation. Kälte-Ind., Beihefte*, **1**, 10-65 (1929).)

d for enthalpy in B.t.u. per pound. (*Courtesy of F. B. Hunt of the Liquid Carbonic Corporation. The data of Plank and Kuprianoff are published in Z. ges. Kälte-Ind., Beihefte*, **1**, 10-65 (1929).)

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